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Sum of segmental bioimpedance analysis during ultrafiltration and hemodialysis reduces sensitivity to changes in body position

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Sum of segmental bioimpedance analysis during ultrafiltration and hemodialysis reduces sensitivity to changes in body position.

Background. Bioimpedance, a noninvasive technique to analyze body composition, has attracted interest in determining body hydration in hemodialysis patients. However, the so-called whole-body (wrist-to-ankle) bioimpedance analysis (WBIA) is sensitive to changes in regional fluid distribution and tends to underestimate fluid changes during ultrafiltration in hemodialysis patients. The aim of this study was to show that volume changes calculated from a new approach, that is, segmental bioimpedance analysis (SBIA), are not affected by changes in body position.

Methods. Ten male patients (age 44 ± 8 years, target weight 70.8 ± 10 kg) were studied during their regular hemodialysis treatment while maintaining either a sitting or a supine body position throughout the study. Extracellular volume was calculated from extracellular resistance obtained from bioimpedance data measured for a range of frequencies (5 to 500 kHz) using the Xitron BIS4000B analyzer. Wrist-to-ankle measurements were compared with segmental arm, trunk, and leg measurements.

Results. Changes in extracellular volume estimated from wrist-to-ankle measurements only reached 80 ± 13% and 65 ± 17% of the actual change in body mass during sitting and supine dialysis treatments, respectively. However, when segmental measurements were analyzed, the calculated change in extracellular volume was 101 ± 6% and 100 ± 3% of the actual change in body mass during the sitting and supine treatments, respectively.

Conclusions. SBIA properly identifies regional fluid changes and provides an appropriate measure of fluid changes caused by ultrafiltration and hemodialysis. The volume estimation based on the sum of segmental bioimpedance measurements is independent of body position, which is a prerequisite for applications in everyday practice.

Bioimpedance analysis (BIA) is a simple and noninvasive method to analyze body composition [1]. However, the accuracy of this method compared with other techniques has been questioned [2–5]. One of the problems of current bioimpedance technique is related to the sensitivity of whole body (wrist-to-ankle) BIA to changes in body position. In a previous article, it was shown that fluid redistribution during orthostasis produced an artifact when wrist-to-ankle measurements, the so-called whole body impedance analysis (WBIA), were used to calculate extracellular volume [6]. It was speculated that this sensitivity was due to redistribution of extracellular fluid among body segments [6]. We showed, to our knowledge for the first time, that extracellular volume was not affected by changes in body position when volume was estimated by a sum of segmental BIA (SBIA) [7]. Bioimpedance could be useful to estimate body hydration, to prescribe fluid removal, and to monitor fluid changes during hemodialysis. A reduced sensitivity to changes in body position has the potential to improve the accuracy of these measurements.

The aim of this study was to introduce the technique using the sum of SBIA to the field of hemodialysis, and to show that changes in extracellular volume calculated from segmental measurements were not affected by changes in body position in a group of hemodialysis patients.

METHODS

Ten end-stage renal disease patients (male; age 44 ± 8 years, range from 33 to 59 years; target weight 70.8 ± 10 kg) were studied during their regular hemodialysis treatment, as approved by the Institutional Review Board of Beth Israel Medical Center. None of the patients had a clinical history of congestive heart failure. Patients were studied during two treatments maintaining either a sitting or a supine body position throughout the treatment. Bicarbonate hemodialysis was provided by a volumetrically controlled hemodialysis machine (2008E) using F80 polysulfone dialyzers (Fresenius Medical Care, Walnut Creek, CA, USA). The length and the circumference of each body segment (arm, trunk, and leg), the

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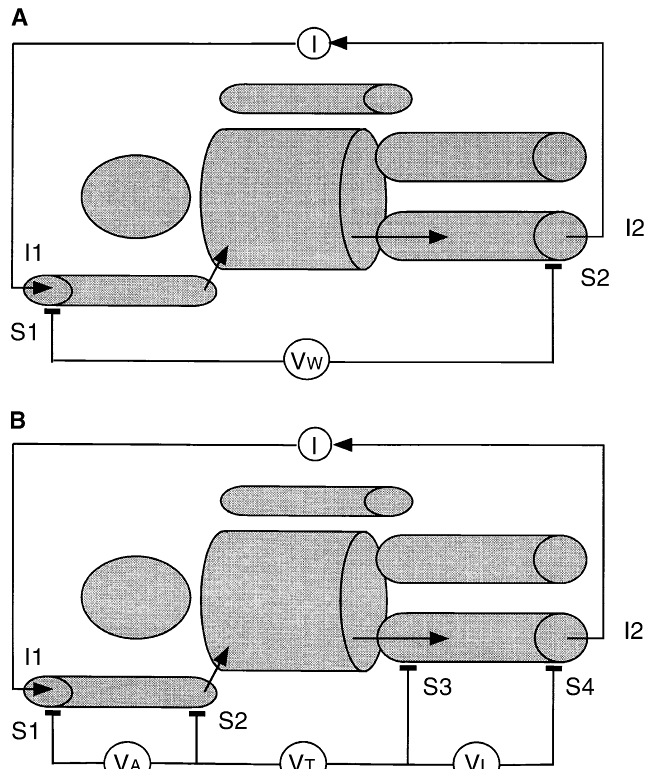

Fig. 1. Bioimpedance measurement. (*A*) Wrist-to-ankle technique where the current is injected from hand to foot and voltage measured between wrist and ankle (V_W). (*B*) Sum of segments technique, where the current is injected from I1 to I2 (hand to foot) and voltage measured between S1 and S2 (arm) (V_A), S2 and S3 (trunk) (V_T), S3 and S4 (leg) (V_L), and S1 and S4 (wrist-to-ankle).

Table 1. Treatment characteristics (N = 10)

		Supine	Sitting
Treatment time	hr	3.2 ± 0.31	3.3 ± 0.35
$Mass_{pre}$	kg	74.3 ± 10	74.7 ± 11
ΔECV_{SS}	liter	3.45 ± 0.85	3.94 ± 0.75
ΔECV_{WB}	liter	2.28 ± 0.87 [a]	3.15 ± 0.35 [a]
ΔM	kg	3.4 ± 0.82	3.94 ± 0.8
UFV	liter	3.55 ± 0.92	3.97 ± 0.65
$\Delta ECV_{SS}/\Delta M$		1.01 ± 0.06	1.00 ± 0.03
$\Delta ECV_{WB}/\Delta M$		0.65 ± 0.17 [a]	0.8 ± 0.13 [a]
$[Na^+]_{pre}$	mEq/liter	136.6 ± 4.2	135.7 ± 3.7
$[Na^+]_{post}$	mEq/liter	140.4 ± 1.2	140.1 ± 3.2
Hypotensive episodes		1	1
$\Delta[Na^+]$	mEq/liter	3.9 ± 4.6	4.3 ± 0.8

Abbreviations are: $Mass_{pre}$, body mass at baseline; Δ, change; ECV, extracellular volume; M, body mass; UFV, ultrafiltration volume; subscript SS, related to the sum of segmental bioimpedence; subscript WB, related to wrist-to-ankle (whole body).
[a] $P < 0.05$, supine vs. sitting

body height, and the body mass were measured before the treatment. Arterial serum $[Na^+]$ was measured at 30-minute intervals using ion-selective electrodes (Ionometer EH-FK; supplied by Fresenius MC, Bad Homburg, Germany).

Bioimpedance measurement

Bioimpedance measurements, using the BIS4000B analyzer (Xitron Technologies, San Diego, CA, USA), were started at the beginning and stopped at the end of hemodialysis without an equilibration phase preceding or following the treatment. In the wrist-to-ankle measurement, two injecting electrodes for applying alternating current were placed on the ipsilateral dorsal surfaces of the hand (I1) and the foot (I2), and two sensing electrodes were placed on the wrist and the ankle (Fig. 1A). In the segmental measurement, four sensing electrodes were placed on the wrist (S1), the shoulder (acromion, S2), the upper anterior iliac spine (S3), and the ankle (malleolus, S4; Fig. 1B). Current was injected for a spectrum of 10 frequencies ranging from 5 to 500 kHz. A digitally controlled switch was used to collect data from three body segments (arm, trunk, and leg) and from wrist-to-ankle measurements [8]. The switch, which was controlled by the interface of a computer, automatically transferred data obtained in each segment to the bioimpedance device. The computer was also used for data acquisition, data storage, and data analysis. The duration for the measurement of one segment was 15 seconds. The duration for a whole cycle of three segmental and one wrist-to-ankle measurement was one minute. In a previous study, the coefficient of variation for the measurement of extracellular resistance in the limbs and in the trunk of normal subjects was determined to be better than ±0.5 and ±1.5%, respectively [7].

Data analysis

Segmental BIA was used to measure segmental extracellular resistance and to estimate extracellular volume in the arm, trunk, leg, and the wrist-to-ankle. Extracellular resistance was determined as the limit resistance at zero frequency from fitting the impedance data according to the modified Cole-Cole model using the software supplied with the impedance device [9]. Extracellular volume for each segment was calculated from the length (L_S), the extracellular resistance (R_S), and the extracellular resistivity ($\rho_{ECV} = 47\ \Omega \cdot cm$) according to Hanai's theory as used elsewhere [9]:

$$ECV_S = k_S \rho_{ECV} \frac{L_S^2}{R_S} \qquad \text{(Eq. 1)}$$

where k_s is a weighting factor accounting for inhomogeneous distribution of current in each segment. In the arm and in the leg, the distribution of electrical current can be assumed to be homogeneous, and $k_s = 1$. In the trunk, the distribution is inhomogeneous. The inhomogeneity of the electric field in the trunk can be taken into account by defining an apparent volume element with homogeneous current distribution, which is approximately one fourth of the extracellular volume in the

Table 2. Extracellular resistance (Ω) during hemodialysis

	Supine			Sitting		
	Start HD	End HD	Change	Start HD	End HD	Change
Arm	209.86 ± 31	237.16 ± 39	27.3 ± 12.5	216.16 ± 25	265.66 ± 25	49.5 ± 4.7
Trunk	45.54 ± 2.4	58.98 ± 2.7	13.44 ± 3.8	43.12 ± 6.8	57.4 ± 7.7	14.28 ± 2.5
Leg	243.02 ± 47	293.56 ± 49	50.54 ± 4.3 [a]	245.22 ± 41	275.38 ± 44	30.16 ± 10 [a]
SS	498.42 ± 74	589.7 ± 77	91.28 ± 15	504.5 ± 70	498.44 ± 72	93.94 ± 12
WB	498.82 ± 75	586.84 ± 74	88.02 ± 11	509.1 ± 75	601.22 ± 70	92.12 ± 17

Abbreviations are: sum of segments (SS), wrist-to-ankle (WB); HD, hemodialysis.
[a] $P < 0.05$, supine vs. sitting

Table 3. Extracellular volume (liters) during hemodialysis

	Supine			Sitting		
	Start HD	End HD	Change	Start HD	End HD	Change
Arm	1.35 ± 0.42	1.2 ± 0.41	0.15 ± 0.07	1.43 ± 0.28	1.15 ± 0.23	0.28 ± 0.06
Trunk	11.92 ± 1.9	9.13 ± 1.5	2.79 ± 0.8	12.37 ± 1.37	9.08 ± 0.56	3.29 ± 0.6
Leg	3.05 ± 1.2	2.54 ± 1.1	0.51 ± 0.14 [a]	3.07 ± 0.75	2.71 ± 0.85	0.36 ± 0.13 [a]
SS	16.33 ± 2.6	12.79 ± 2.2	3.45 ± 0.85	16.88 ± 1.4	12.94 ± 1.2	3.94 ± 0.27
WB	20.95 ± 4.4	18.67 ± 3.65	2.28 ± 0.87 [a]	21.23 ± 3.6	18.08 ± 3.4	3.15 ± 0.35 [a]

[a] $P < 0.05$, supine vs. sitting, sum of segments (SS), wrist-to-ankle (WB)

trunk. Therefore, a factor $k_s = 4$ is used for the volume calculation in the trunk [10]. The sum of segmental extracellular volume was calculated as:

$$ECV_{SS} = 2(ECV_{arm} + ECV_{leg}) + ECV_{trunk} \quad \text{(Eq. 2)}$$

Wrist-to-ankle extracellular volume was estimated from body mass (M), body height (H), and wrist-to-ankle resistance (R_{WB}), as described elsewhere [9]:

$$ECV_{WB} = k_{ECV}\left(\frac{H^2\sqrt{M}}{R_{WB}}\right)^{2/3} \quad \text{(Eq. 3)}$$

where k_{ECV} is a function of resistivity, body density, and body geometry.

Results are reported as mean values ± SD and are compared by the Student's *t*-test and by Bland-Altman analysis. A probablility of $P < 0.05$ was considered significant to reject the null hypothesis ($H_0 = 0$). The null hypothesis assumes that measurements obtained with different methods belong to the same sample, that is, they do not differ from each other.

RESULTS

A summary of treatment characteristics for patients studied in the supine and sitting body positions is given in Table 1. Predialysis mass, mean mass loss, and mean ultrafiltration volume were not different between the two groups studied. During treatments, $[Na^+]$ increased by 3.9 ± 4.6 and 4.3 ± 0.8 mEq/liter in treatments with both the supine and sitting body positions. The frequency of symptomatic hypotension and the $[Na^+]$ increase was not different between the two groups (Table 1).

An important electrical relationship was confirmed in this study. Wrist-to-ankle and sum of segmental resistances only differed by 0.5% of the reading. The small difference can be explained by the measuring procedure, which does not take simultaneous segmental and wrist-to-ankle readings, but takes serial measurements in 15-second intervals. Small changes occurring within one minute are responsible for the small deviation observed between both approaches. In the supine body position and before the start of ultrafiltration, 42% of extracellular resistance were located in the arm, 9% in the trunk, and 49% in the leg, respectively. The contribution of segmental resistance was similar at the end of the treatment and not different in tests done in the sitting position. However, the change in leg resistance was significantly smaller in the sitting compared with supine patients. Ultrafiltration during hemodialysis caused a general increase in segmental and wrist-to-ankle resistance. The absolute increase was higher in the leg but smaller in the trunk when patients were treated in a supine body position (Table 2). Because of ultrafiltration during hemodialysis, extracellular volume decreased in all segments and in the wrist-to-ankle measurement. In addition, a significant difference was also observed in leg and trunk volume changes between patients treated in supine and sitting body position. With the same amount of fluid removed, the decrease in extracellular volume was larger in the leg (−0.51 ± 0.14 vs. −0.36 ± 0.13 liter, $P < 0.05$) but smaller in the trunk (−2.79 ± 0.8 vs. −3.29 ± 0.6 liter, $P < 0.05$) when patients were ultrafiltered in the supine body position (Table 3). Extracellular volume estimated from wrist-to-ankle resistance systematically exceeded the sum of segmental volumes by 4 to 5 liters.

The relationship between extracellular volume changes and ultrafiltration volume was close to the line of identity for segmental measurements. However, volume changes were systematically underestimated by wrist-to-ankle measurements (Fig. 2). Additional analysis using the Bland-Altman approach showed no discrepancy for segmental measurements in the sitting (−0.04 liter) or in supine body position (−0.1 liter), respectively (Fig. 3 A, C). Wrist-to-ankle measurements, in contrast, showed a discrepancy of −0.81 liters in sitting and an even larger discrepancy of −1.28 liters in the supine body position (Fig. 3 B, D).

The fraction (F) of extracellular volume change measured by the bioimpedance technique relative to the mass loss was calculated as the ratio of segmental ($F_{ss} = \Delta ECV_{SS}/\Delta M$) or wrist-to-ankle ($F_{WB} = \Delta ECV_{WB}/\Delta M$) extracellular volume to the mass loss ΔM, respectively. F_{SS} was close to identity (1.01 ± 0.06 vs. 1.00 ± 0.03, P = NS) with both the supine and sitting treatments when volume changes were calculated from sum of the segmental measurements. When volume changes were calculated from wrist-to-ankle measurements, fluid removal was systematically underestimated with both the sitting and supine treatments ($P < 0.05$). The underestimation was larger when treatments were done in a supine (0.65 ± 0.17 vs. 0.80 ± 0.13, $P < 0.05$) rather than in a sitting body position (Fig. 4).

DISCUSSION

Changes in body position have been known to affect the measurement of extracellular volume by wrist-to-ankle BIA [6, 7]. An error of up to 1 liter can be observed with this technique, even though extracellular volume can be assumed to remain constant during a change in body position. The apparent error in intracellular volume is even larger—and goes in the same direction—so that body water balance is not maintained when investigated by wrist-to-ankle BIA [6]. In a previous study, we showed that this error is almost abolished with a segmental bioimpedance approach, which measures the sum of segmental extracellular volumes [7, 11]. In our current article, we show that the ultrafiltration-induced change in extracellular volume in hemodialysis patients measured by the segmental approach is insensitive to changes in body position. This is a prerequisite for noninvasive and continuous fluid monitoring in patients who change their body position and in whom large changes in extracellular volume are to be expected because of ultrafiltration.

Ultrafiltration during hemodialysis caused a general increase in segmental and wrist-to-ankle resistance. The larger increase in leg resistance with supine body position can be explained by enhanced movement of fluid from peripheral to central body compartments. Consequently, central refilling was improved, which could be observed by a reduced decrease in trunk resistance with supine body position. However, in treatments done in the sitting

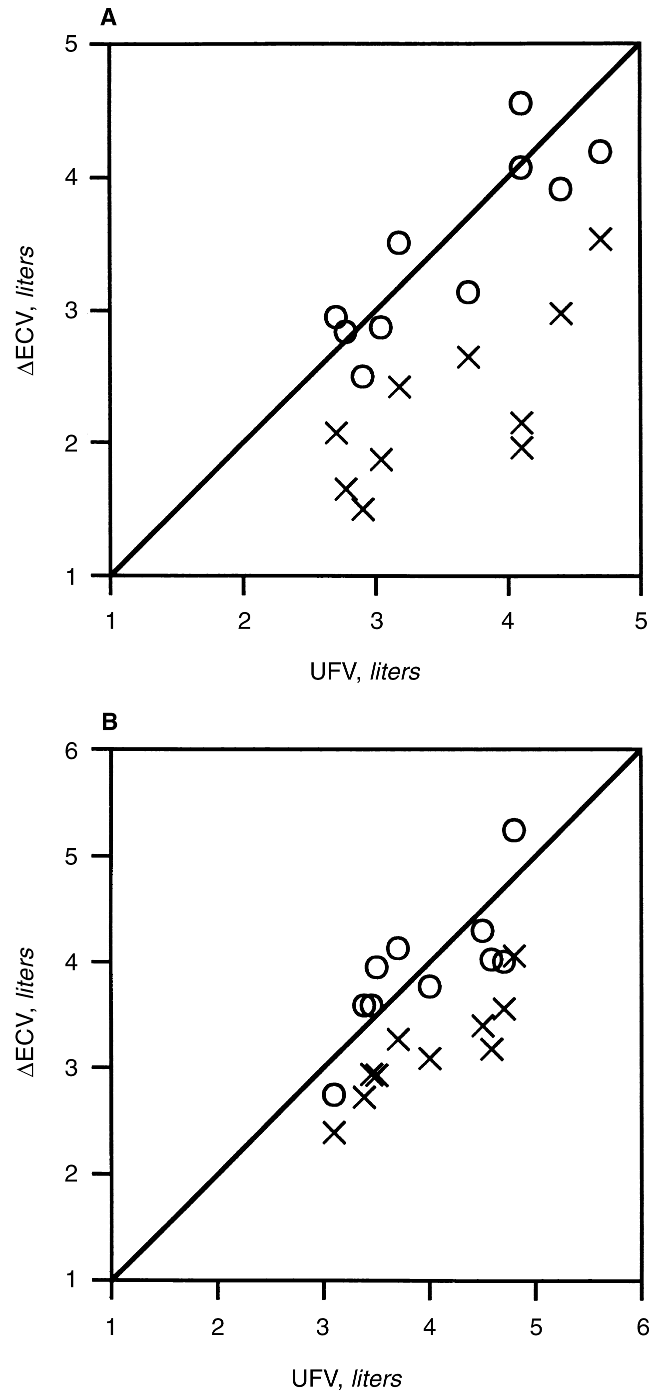

Fig. 2. Changes in extracellular volume (ΔECV) and ultrafiltration volume (UFV). Identity plot of ΔECV calculated from segmental (SBIA; ○) or wrist-to-ankle (WBIA; ×) measurements compared with ultrafiltration volume in treatments with different body position. (*A*) Supine body position. (*B*) Sitting body position.

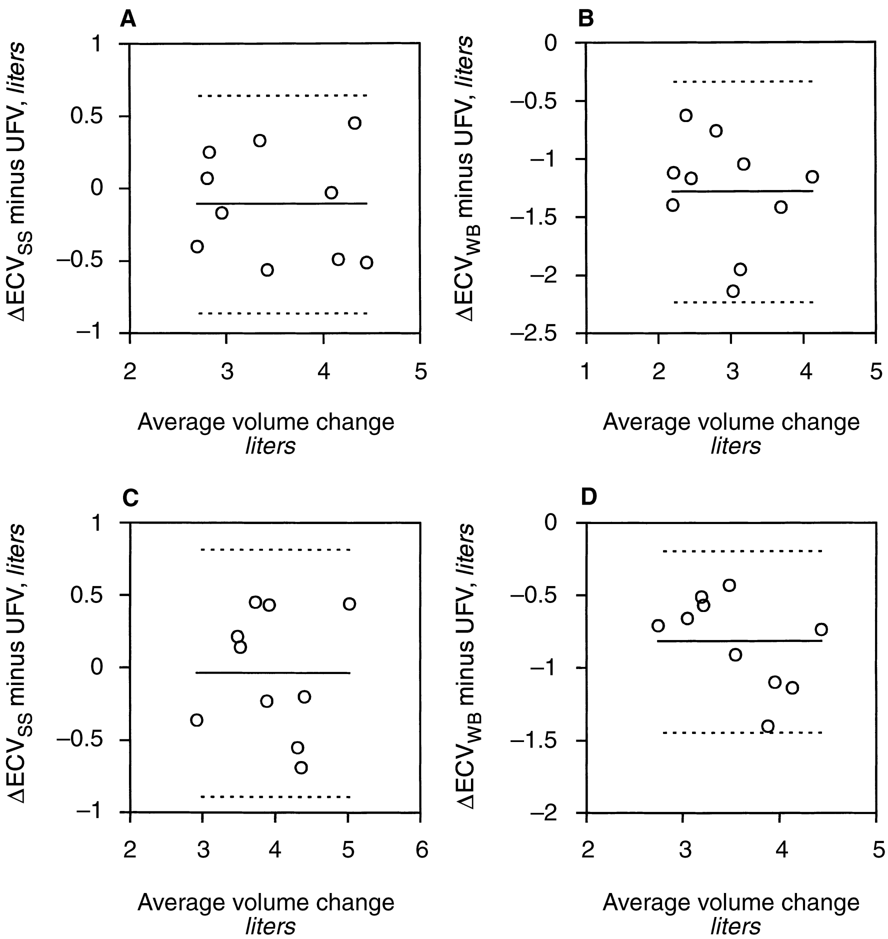

Fig. 3. Change in extracellular volume (ΔECV) and ultrafiltration volume (UFV). Bland-Altman analysis (mean difference ± 2 SD) of ΔECV calculated from segmental (ΔECV_{SS}) or wrist-to-ankle (ΔECV_{WB}) measurements compared with ultrafiltration volume in treatments with different body position. (*A* and *B*) Supine body position. (*C* and *D*) Sitting body position. Panels A and C denote the sum of segments analysis, while panels B and D are whole body analysis. The circles represent the data, solid line the mean difference (d), and the dashed line is ± 2 SD.

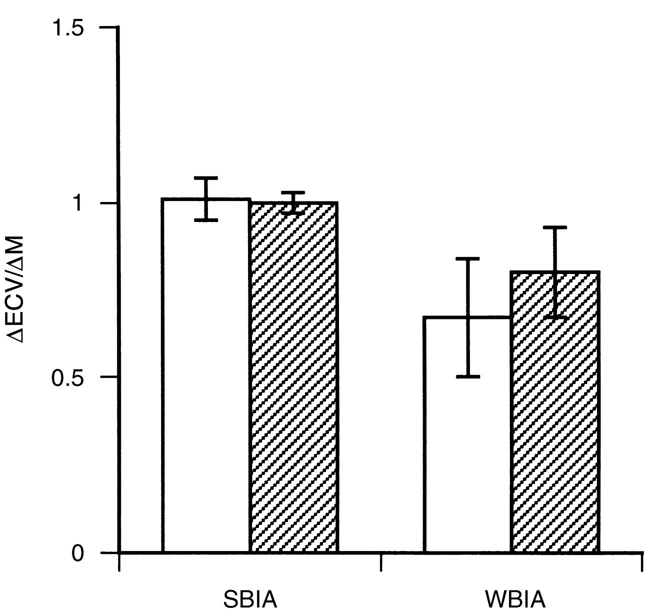

Fig. 4. Extracellular volume change relative to mass loss by segmental (SBIA) and wrist-to-ankle (WBIA) bioimpedance analysis with the patient in the supine (□) or sitting (▨) position.

body position, a significant amount of extracellular fluid was sequestered in the legs (Table 3).

Why are the volume estimations different?

The sum of segmental resistances is equal to wrist to ankle resistance, but the volume estimation was different between wrist-to-ankle and the sum of segments techniques. Wrist-to-ankle BIA uses measurements obtained from only part of the body. It is generally assumed that the limbs are symmetric. Wrist-to-ankle bioimpedance measurements are usually done on one side of the body. In general, this approach is acceptable but may cause problems in hemodialysis patients in which significant differences have been observed because of the peripheral access, which may be responsible for venous outflow obstruction and edema formation. It is well known that the limbs are responsible for approximately 90% of resistance measured between the ipsilateral wrist and ankle; however, the limb volume on one side of the body only constitutes 15% of the extracellular volume [12]. The differences between the sum of segments and the wrist to ankle approach can be clarified by the different contribution of each body segment to wrist-to-ankle resistance

Table 4. Resistance normalized to volume (α_n) during hemodialysis

	Supine			Sitting		
	Start HD	End HD	Change	Start HD	End HD	Change
Arm	12.85 ± 2.3	18.54 ± 2.9	5.69 ± 0.7	12.81 ± 2.6	20.53 ± 3.4	7.72 ± 1.1
Trunk	11.15 ± 2.2	18.45 ± 2.5	7.29 ± 0.8	2.55 ± 0.7	4.44 ± 0.4	1.88 ± 0.3
Leg	14.88 ± 3.6	22.95 ± 3.4	8.07 ± 0.6	14.53 ± 0.9	21.28 ± 0.8	6.75 ± 0.6
SS	38.89 ± 5.3	59.94 ± 6.4	21.05 ± 1.7	29.89 ± 1.6	46.25 ± 4.8	16.36 ± 0.5
WB	23.81 ± 2.1	31.4 ± 1.9	7.62 ± 0.5	23.98 ± 2.4	33.25 ± 1.7	9.27 ± 0.4

Abbreviations are: SS, sum of segments; WB, wrist-to-ankle.

and to whole body extracellular volume. The amount of resistance provided per unit extracellular volume varies in the different segments. We define this ratio as normalized resistance (α; discussed in **Appendix A** and shown in equation 4). For instance, at the beginning of hemodialysis, the resistance per volume is 80 and 15 Ω/liter in the leg and in the trunk, respectively (Table 4). A reduction in the volume by 1 liter will increase the resistance by approximately 80 Ω in the leg, but by approximately 15 Ω in the trunk. Accordingly, if the change in resistance is the same in both segments, the volume change will be different. Thus, if a change in resistance is measured for the sum of segments (= wrist-to-ankle), the volume change cannot be determined for the sum of segmental volumes. However, if resistance is measured in segments in which a homogenous normalized resistance can be assumed, the change in volume can be calculated from a change in resistance. In fact, a uniform normalized resistance is a prerequisite to calculate the conductor volume from conductor resistance. The relationship of extracellular volume estimation between sum of segmental and wrist-to-ankle BIA can be explained using equation 9 (discussed in **Appendix A**). Because the volume estimated from wrist-to-ankle resistance was larger than that of the sum of segments (Table 3), the normalized resistance from wrist to ankle (α_{WB}) is smaller than that of the sum of segments (α_{SS}). However, α should have the same value measured by both techniques. The difference between α_{SS} and α_{WB} is related to the erroneous assumption of a uniform distribution of fluid and resistance in all body segments. The change in extracellular volume calculated from wrist-to-ankle BIA was smaller than ultrafiltration volume or mass loss both in the supine and sitting body positions. With sum of segments measurements, however, the calculated volume change was almost equal to ultrafiltration volume or mass loss. The difference in calculated volume changes between wrist-to-ankle and sum of segments technique can also be explained using normalized resistances, as described in equation 11 (discussed in **Appendix A**).

Segmental versus sum of segments technique

This technique is based on resistance measurements in all segments to determine segmental volume and the sum of segmental volumes. We call this technique "sum of SBIA," which is different from SBIA as used previously. The difficulties associated with wrist-to-ankle BIA have been recognized by many investigators, and it was therefore suggested that bioimpedance be measured in selected body segments only [13–15]. The difficulties associated with this approach can be depicted using data from this study where leg resistance increased by 50 or 30 Ω with ultrafiltration done in supine or sitting body position. The difference of 20 Ω accounts for more than 20% of the wrist-to-ankle resistance change. It is difficult to imagine how an isolated segmental measurement of resistance could be used to estimate body hydration successfully.

The difficulty with wrist-to-ankle BIA is related to the geometry of the trunk and to the nonuniform distribution of the electrical current in the different segments of the body [16, 17]. The electrical current is usually injected on one side on the top and on the bottom edge of the trunk. The trunk cylinder is too short compared with its cross-sectional area for end effects to be negligible. For example, the resistance measured between pairs of equidistant electrodes mounted on the back and the front of the trunk in sagittal planes decreases with increasing distance from the site of current injection [10]. Because of this inhomogeneity, a volume equivalent to approximately one fourth of the trunk extracellular volume is measured when electrodes are placed on the shoulder and on the iliac crest of the subject. Therefore, the extracellular volume calculated in the trunk must be corrected by a factor of four (equation 1) [10].

The term "whole body BIA" used for the approach to derive extracellular volume from the measurement of one conductor, that is, wrist to ankle, is a misnomer. Indeed, because hands, feet, and head are always excluded from direct measurement, none of the current techniques measure all body segments or the whole body. In addition, most of the time, only one side of the body is measured, which may cause significant errors if body fluids have not equilibrated between the segments. This is one of the reasons that wrist-to-ankle measurements tend to underestimate fluid removal during ultrafiltration [18]. On the other hand, segmental techniques that focus on local characteristics are prone to changes in regional fluid distribution. Therefore, to compensate for errors made with so-called whole and segmental measurements, we propose the use of the term "sum of segmental bioimpedance analysis" (SBIA). This approach provides estimates of extracellular volume during ultrafiltration and hemodialysis that are independent of changes in body position. This is a prerequisite for noninvasive and continuous fluid monitoring during hemodialysis in which changes in body position are common.

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APPENDIX A

In each segment the ratio of resistance to extracellular volume ($\alpha = R/V$) is defined as normalized resistance (α):

$$\alpha = \frac{R}{V} \quad \text{(Eq. 4)}$$

The sum of segmental volume (V_{SS}) is given by

$$V_{SS} = \frac{R_{SS}}{\alpha_{n,SS}} \quad \text{(Eq. 5)}$$

where $\alpha_{n,SS}$ is the sum of segmental resistance normalized to volume and weighted for the volume fraction

$$\alpha_{n,ss} = \sum_i \alpha_i \frac{V_i}{V_{ss}}, \qquad i = \text{arm, trunk, leg} \quad \text{(Eq. 6)}$$

According to equation 4, wrist-to-ankle resistance normalized to volume can be calculated as

$$\alpha_{WB} = \frac{R_{WB}}{V_{WB}} \quad \text{(Eq. 7)}$$

Because $R_{WB} = R_{SS}$ (Table 2), a combination of equations 5 and 7 yields

$$V_{WB} = V_{SS}\frac{\alpha_{n,SS}}{\alpha_{WB}} \quad \text{(Eq. 8)}$$

Because $V_{WB} > V_{SS}$ (Table 3), therefore $\alpha_{SS}/\alpha_{WB} > 1$.

The calculated volume change ΔV derived from a change in wrist to ankle or sum of segmental resistance is given as

$$\Delta V = V_0 - V_t = \frac{R_0}{\alpha_0} - \frac{R_t}{\alpha_t} = \frac{R_0 - \lambda R_t}{\alpha_0} \quad \text{(Eq. 9)}$$

where the index 0 and t refers to the beginning and the end of the fluid removal, respectively, and where λ is the ratio of normalized resistance before and after the fluid removal

$$\lambda = \frac{\alpha_0}{\alpha_t} \quad \text{(Eq. 10)}$$

However, the difference in ΔV between the wrist-to-ankle and the sum of segments measurement derived from equation 10 is given as

$$\Delta V_{SS} - \Delta V_{WB} = \frac{R_0 - \lambda_{SS}R_t}{\alpha_{n,SS,0}} - \frac{R_0 - \lambda_{WB}R_t}{\alpha_{WB,0}} \quad \text{(Eq. 11)}$$

The change in volume from wrist-to-ankle measurement is smaller than the change by sum of segments measurement and can be explained as follows: Assume that $\lambda_{WB} = \lambda_{SS}$, then the value of $\Delta V_{SS} - \Delta V_{WB}$ depends on $\alpha_{n,SS,0}$ and $\alpha_{WB,0}$. Because $\alpha_{n,SS}$ is larger than α_{WB}, ΔV_{SS} is larger than ΔV_{WB}. However, because $\lambda_{WB} > \lambda_{SS}$ (Table 5), ΔV_{SS} will be much larger than ΔV_{WB}.

Table 5. Relative change of normalized resistance (λ) during hemodialysis

	λ_{supine}	$\lambda_{sitting}$	$\lambda_{sitting} - \lambda_{supine}$
Arm	0.69	0.62	−0.07
Trunk	0.6	0.58	−0.03
Leg	0.65	0.68	0.03
SS	0.65	0.65	0.00
WB	0.76	0.72	−0.04

Abbreviations are: SS, sum of segments; WB, wrist to ankle.

APPENDIX B

Abbreviations used in this article are: α_n, resistance normalized to volume and weighted for volume fraction (equation 6); ECV, extracellular volume; ΔECV, change in extracellular volume estimated from bioimpedance analysis; F, ratio of extracellular volume change to mass change; α, resistance normalized to volume (equation 4); f, current frequency; H, body height (equation 3); k, weighting factor (equation 1); λ, ratio of normalized resistance (equation 10); L, length of segment (equation 1); M, body mass; ΔM, change in body mass; R, resistance; ρ_{ECV}, extracellular resistivity (equation 1); subscript s, related to segmental measurement; subscript SS, related to sum of segmental bioimpedance analysis; subscript t, related to end of observation phase; t, time; UFV, ultrafiltration volume; V, volume; ΔV, change in volume; subscript WB, related to wrist-to-ankle (whole body) bioimpedance analysis; Z, electrical impedance; and subscript 0, related to beginning of observation phase.

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